M X Rays of Yb and Lu Induced by Ion Impacts

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I. 12 M X Rays of Yb and Lu Induced by Ion Impacts

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Thick targets of metallic Yb and Lu, YbF_3, Yb_2O_3 and Lu_2O_3 were bombarded by 3 MeV/amu protons and ^3He ions, and the induced M x rays of Yb and Lu measured by using a Johansson type-crystal spectrometer. The spectra of M x-rays from Yb and Lu induced by proton impacts are shown in Fig. 1 (a) and (b), respectively, where the total counts of M_β-x rays are normalized by unity. It is seen from this figure that there is a big difference between the spectrum of Yb metal and those of Yb compounds, especially at the M_α-line, while the spectrum of Yb oxcide is very similar to that of Yb fluoride. In contrast to the evidence that the spectrum of Lu metal is coincident with that of Lu fluoride, the shape of the spectrum of Yb metal is similar to that of Lu. The difference in the Yb-M_α lines may be understood in terms of self-absorption effect within target. In Yb compounds there is a vacancy in the 4f orbital. This vacancy induces a strong self-absorption due to a dipole transition (e.g. $3d \rightarrow 4f$) in the target, while there are no vacancies in the 4f-orbital of the metal.[1]

We have analyzed M x-ray spectra by a peak separation method using a least-squares fitting with the Voigt function.[2] Fig. 2 shows the peak separated spectrum for Yb metal. On the M_α and M_β lines, the first, second and third peaks from left to right are assumed tentatively to correspond to the transitions of $3d^{-1}4f^{14} \rightarrow 4f^{13}$, $3d^{-1}4f^{13} \rightarrow 4f^{12}$ and $3d^{-1}4f^{14}(4s, 4p \text{ or } 4d)^{-1} \rightarrow 4f^{13}(4s, 4p \text{ or } 4d)^{-1}$ respectively. This order of x-ray energy is consistent with the calculations based on the eigen values of the Herman and Skillman wave function.[3] The production cross sections of $3d^{-1}4f^{14}$, $3d^{-1}4f^{13}$ and $3d^{-1}4f^{14}(4s, 4p \text{ or } 4d)^{-1}$ states for Yb metal are given by[4],

$$\sigma(3d_{5/2}^{-1}4f^{14}) \fallingdotseq (1-Z_p^2P_N)^{32}\sigma_{M_5}^i \tag{1}$$

$$\sigma(3d_{5/2}^{-1}4f^{13}) \fallingdotseq (1-Z_p^2P_N)^{32}(S_{M_4\rightarrow M_5N_{6,7}}\sigma_{M_4}^i + S_{M_3\rightarrow M_5N_{6,7}}\sigma_{M_3}^i + S_{M_2\rightarrow M_5N_{6,7}}\sigma_{M_2}^i + S_{M_1\rightarrow M_5N_{6,7}}\sigma_{M_1}^i + 14Z_p^2P_N\sigma_{M_5}^i/(1-Z_p^2P_N)) \tag{2}$$

$$\sigma(3d_{5/2}^{-1}(4s,\ 4p\ \text{or}\ 4d)^{-1}) \fallingdotseq (1-Z_p^2P_N)^{32}(S_{M_3\to M_5N_{1\sim5}}\sigma^i_{M_3} + S_{M_2\to M_5N_{1\sim5}}\sigma^i_{M_2}$$

$$+ S_{M_1\to M_5N_{1\sim5}}\sigma^i_{M_1} + 18Z_p^2P_N\sigma^i_{M_5}/(1-Z_p^2P_N)) \tag{3}$$

$$\sigma(3d_{3/2}^{-1}4f^{14}) \fallingdotseq (1-Z_p^2P_N)^{32}\sigma^i_{M_4} \tag{4}$$

$$\sigma(3d_{3/2}^{-1}4f^{13}) \fallingdotseq (1-Z_p^2P_N)^{32}(S_{M_3\to M_4N_{6,7}}\sigma^i_{M_3} + S_{M_2\to M_4N_{6,7}}\sigma^i_{M_2}$$

$$+ S_{M_1\to M_4N_{6,7}}\sigma^i_{M_1} + 14Z_p^2P_N\sigma^i_{M_4}/(1-Z_p^2P_N)) \tag{5}$$

and

$$\sigma(3d_{3/2}^{-1}(4s,\ 4p\ \text{or}\ 4d)^{-1}) \fallingdotseq (1-Z_p^2P_N)^{32}(S_{M_3\to M_4N_{1\sim5}}\sigma^i_{M_3} + S_{M_2\to M_4N_{1\sim5}}\sigma^i_{M_2}$$

$$+ S_{M_1\to M_4N_{1\sim5}}\sigma^i_{M_1} + 18Z_p^2P_N\sigma^i_{M_4}/(1-Z_p^2P_N))\ , \tag{6}$$

where σ_{M_k} and $S_{M_i\to M_jN_k}$ represent the ionization cross sections of the M_k-shell[5] induced by 3 MeV proton impact and the Coster-Kronig coefficient for the transition of M_i-shell hole to M_j- and N_k-shell holes[6], respectively, P_N denotes an ionization probability of N-shell electrons[7] at zero impact parameter for 3 MeV proton and Z_p means the atomic number of incident ion.

By using equations (1) and (4), we can estimate the intensity of x rays due to $3d_{5/2}^{-1}4f^{14} \to 4f^{13}$ or $3d_{3/2}^{-1}4f^{14} \to 4f^{13}$ transition in the case of Yb thick metallic target;

$$N(3d_{5/2}^{-1}4f^{14} \to 4f^{13}) = \omega_5 \frac{\Gamma^R_{M_5-N_{6,7}}}{\Gamma^R_5}\ \sigma(3d_{5/2}^{-1}4f^{14})/\sigma_p(\hbar\omega_\alpha) \tag{7}$$

or

$$N(3d_{3/2}^{-1}4f^{14} \to 4f^{13}) = \omega_4 \frac{\Gamma^R_{M_4-N_{6,7}}}{\Gamma^R_4}\ \sigma(3d_{3/2}^{-1}4f^{14})/\sigma_p(\hbar\omega_\beta)\ . \tag{8}$$

In equations (7) and (8), ω_k represents the fluoresence yields for M_k-shell[8], Γ^R_k and $\Gamma^R_{M_k-N_{6,7}}$ are the total radiative width of M_k-shell and the partial radiative width for M_k-$N_{6,7}$ transition, respectively.[9] $\sigma_p(\hbar\omega_\alpha)$ $(\sigma_p(\hbar\omega_\beta))$ denotes the photo cross sections[10] for M_α-$(M_\beta$-$)$ x rays. The intensity of the M_α- or M_β- satellite line can also be estimated in the similar as in Eqs. (7) and (8). The calculations of x-ray intensity for each line are compared in Fig. 3 with the experimental results obtained by peak fitting for the cases of proton impact (Z_p=1) and ^{3}He ion impact (Z_p=2). Note that the theoretical intensity is normalized by the experimental one at the $3d_{5/2}4f^{14} \rightarrow 4f^{13}$ transition line. On the M_α-lines, the theory reproduces quite well experimental points for both proton and ^{3}He ion impacts. This result supports our tentative assignments for x-ray lines.

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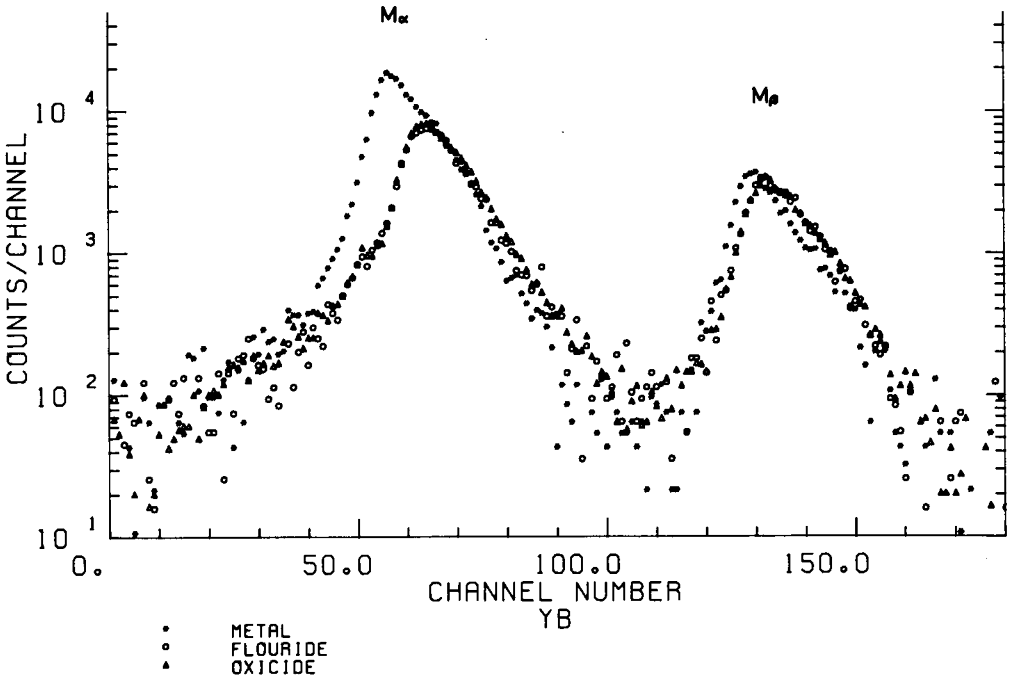

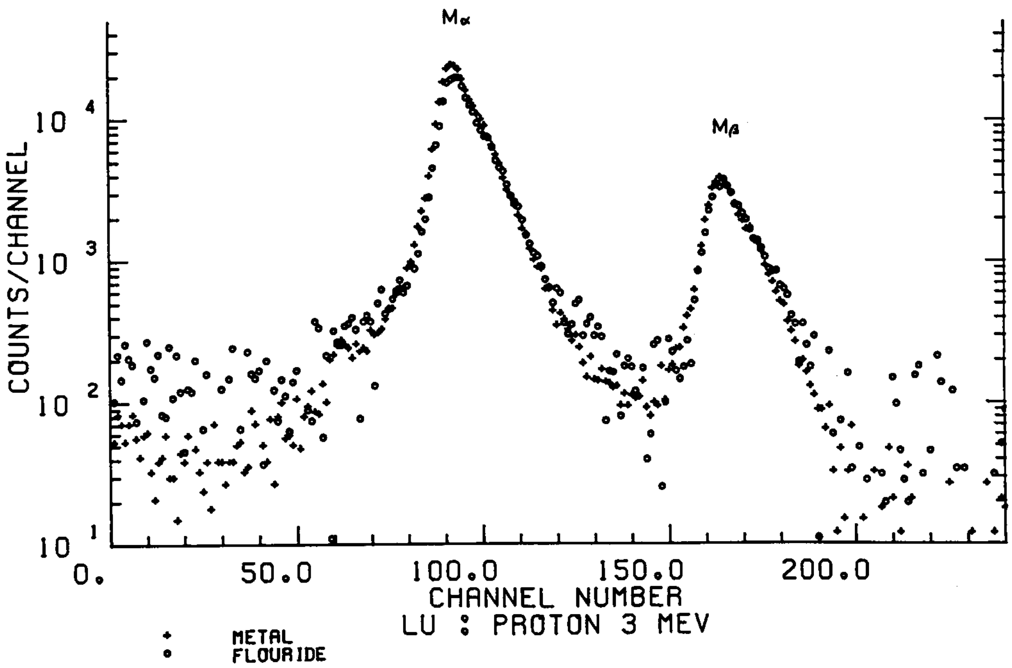

Fig. 1. M x-ray spectra induced by 3 MeV proton impacts for metal, fluoride and oxcide of Yb (a) and metal and fluoride of Lu(b).

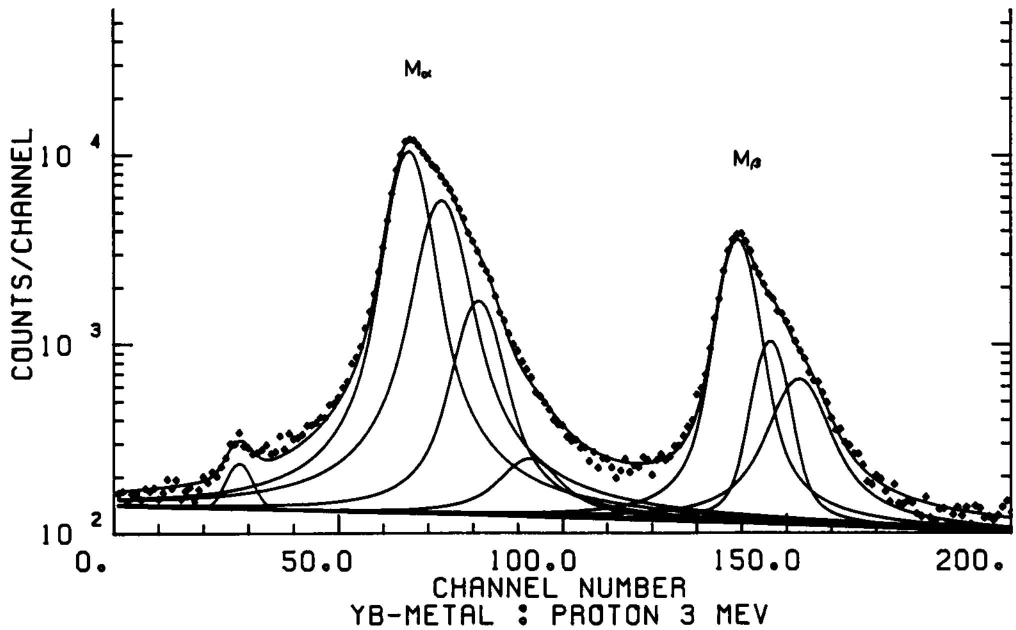

Fig. 2. Peak fitting spectrum of Yb metal. The x-ray spectrum is divided by into various x-ray lines by least-squares fitting with the voigt function.

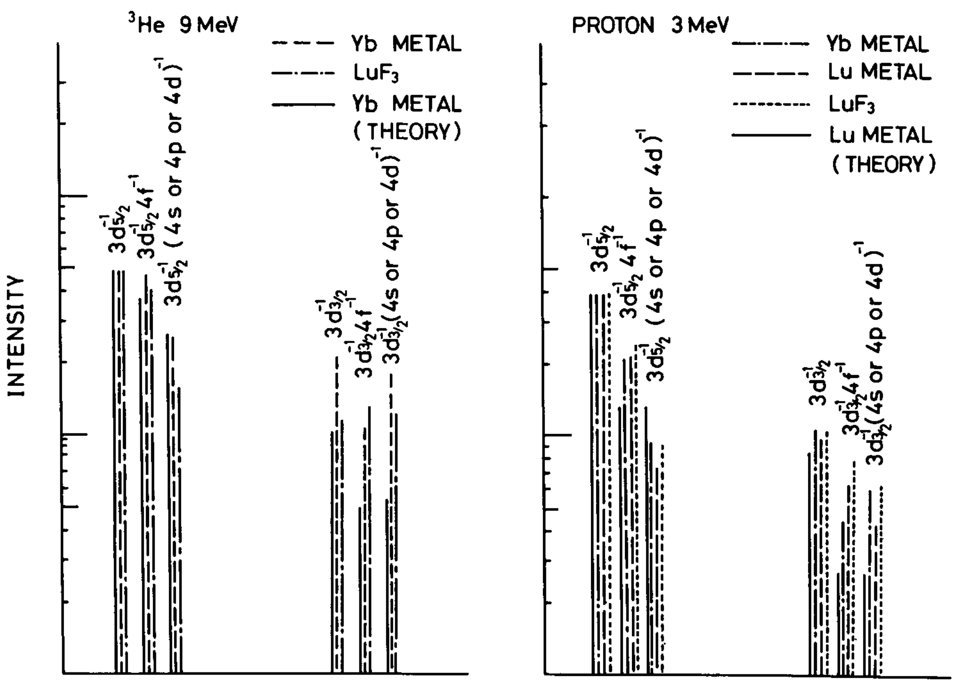

Fig. 3. Comparison between theoretical intensity of x-ray line and experimental intensity.